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NONCONTACT ACOUSTO-ULTRASONICS FOR MATERIAL CHARACTERIZATION

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ABSTRACT

A NdYAG 1064 nm, laser pulse was employed to produce ultrasonic waves in specimens of SiC/SiC and SiC/Ti 6-4 composites which are high temperature materials of interest for aerospace applications. Air coupled transducers were used to detect and collect the signals used for acousto-ultrasonic analysis. Conditions for detecting ultrasonic decay signals were examined. The results were compared to those determined on the same specimens with contact coupling. Some noncontact measurements were made employing conventional air focused detectors. Others were performed with a more novel micromachined capacitance transducer.

Concerns of the laser-in technology include potential destructiveness of the laser pulse. Repeated laser pulsing at the same location does lead to deterioration of the ultrasonic signal in some materials, but seems to recover with time. Also, unlike contact A-U, the frequency regime employed is a function of laser-material interaction rather than the choice of transducers.

Concerns of the air coupled-out technology include the effect of air attenuation. This imposes a practical upper limit to frequency of detection. In the case of the experimental specimens studied ultrasonic decay signals could be imaged satisfactorily.

INTRODUCTION

High temperature materials are of increasing importance in development of more efficient engines and components for the aeronautics industry. In particular, ceramic matrix composite (CMC) and metal matrix composite (MMC) structures are under active development for these applications [1].

The acousto-ultrasonic (A-U) method has been shown to be useful for assessing mechanical properties in composite structures [1-8]. For example, plate wave analysis has been shown to be useful [1, 9,10] for characterizing composites in terms of the elastic moduli. Similarly, Ultrasonic Decay rates (UD) obtained from A-U signals can monitor the material/mechanical state in composites [11-14], for example in terms of residual strength or crack density.

It is desirable to monitor changes in material/mechanical properties which occur during thermomechanical testing. It is also desirable to monitor the health of components whose geometry or position make them not readily accessible to conventional ultrasonic probes. For these and other similar applications it would be useful to apply A-U by means that do not require direct coupling to the surface of a subject to be interrogated [15].

The use of a laser as a remote ultrasonic input source and also as an ultrasound detector have been under investigation for a number of years [16-19]. The use of an ultrasonic transducer, coupled thorough an air gap has also been under study [20-21].

It has so far been the experience in this laboratory that the use of a laser as an ultrasonic source has been more successful than as an output device. On the other hand, the author has been more successful using an air-coupled piezoelectric transducer as an output device than as input. For this reason we have studied the combination laser-in air coupled transducer-out. This combination has already been demonstrated as capable of determining the lowest mode Antisymmetric Plate Wave Velocity in Ceramic Matrix Composite Tensile samples [22]. The present work extends the use of the pulsed Neodymium:Yttrium aluminum Garnet (NdYAG) laser as the input ultrasonic source in conjunction with an air-coupled transducer as the detector for the measurement of UD rates in composites.

THEORETICAL

In the present work UD rates are calculated employing laser-in air coupled-out waveforms. In order to produce the desired exponentially decaying signals, ultrasonic data must be collected in an ultrasonic wavelength, λ , to specimen thickness, h , ratio regime

$$\lambda / h \geq \sim 2. \quad (1)$$

Since the wavelength, λ , can be expressed in terms of the longitudinal velocity, V_L , and the applied frequency, f , Eq. (1) can be rearranged to give:

$$V_L / fh \geq \sim 2. \quad (2)$$

VL, is dependent on material properties and h is dependent upon specimen geometry. These factors combine to determine the frequency, f, that one applies. For given material properties, Eq. (2) imposes a maximum on the product of the applied frequency and the specimen thickness h. Typical experimental coupons we employ in this work tend to be about as thin as one is likely to encounter. Application to industrial quality control or hardware health monitoring would probably involve larger h values and therefore lower frequencies. This seems to be advantageous in noncontact A-U since lower frequency, especially for air coupling, will allow recovery of stronger signals, as was observed, for example, in the work for [13]. Stronger signals lead to greater precision.

An A-U signal Φ , is, as any propagating wave, a function of both distance x, as well as time t:

$$\Phi = \Phi(x, t) \quad (3)$$

Experimentally, however, the distance between the point of entry and point of detection of the ultrasound is held constant and the signal can be treated as a function, $\Psi(t)$, of time only. In terms of its Fourier transform, $\Psi(t)$ is expressed as [23]

$$\Psi(t) = \int F(f) e^{i2\pi ft} df \quad (4)$$

as a function of frequency, f where $F(f)$ is the magnitude spectrum of $\Psi(t)$. It is an array obtained from the Fast Fourier transform (FFT) of the digitally encoded time signal. The square of the elements of this array measures the energy in the signal as a function of f. For the exponentially decaying signal the squared magnitude array is assumed to have the form

$$[F(f)]^2 = [F_0(f)]^2 e^{-\beta(f)t}. \quad (5)$$

The frequency dependent variable, $\beta(f)$, is the UD decay rate. The original time function, $\Psi(t)$ is not a simple exponential as long as β depends on frequency. But it approximates close enough to identify the portion of the signal that is of interest.

In general, the observed $\beta(f)$ is composed of several components which contribute to energy loss:

$$\beta(f) = \sum \beta_i(f) \quad (6)$$

Typically, energy loss is the result of: (1) a contact-coupled transducer, (2) the support structure of an engine component or specimen fixture, as well as (3) the losses in the subject under investigation. Let this last term, determined by the material-mechanical condition of the subject, be called $\beta_{MM}(f)$. It is the one of interest. Changes in $\beta_{MM}(f)$ are due to changes in the material-mechanical condition of the subject. For this reason the UD rate, $\beta(f)$, that is calculated is most useful for comparing the condition of the subject before and after thermomechanical, or other, stress exposure [14]. With experimental parameters held constant, the difference between the after and the before UD rates is:

$$\beta(f)_{\text{after}} - \beta(f)_{\text{before}} = \Delta\beta(f) = \Delta\beta_{MM}(f) \quad (7)$$

The induced change in the UD rate is a result of degradation due to mechanical loads or enviromental exposure.

EXPERIMENTAL

An approximate theory has been worked out for Lamb waves in composite structures [2]. It was applied to ceramic matrix composites to identify the first symmetric and first antisymmetric mode pulses, and to determine propagation velocities [10]. The experimental work in [10] was performed using transducers coupled to the specimen surfaces through elastomer couplant pads. A recent study [22] reported on the easily identified lowest mode antisymmetric pulse, and employed laser-in air coupled out A-U. This work was a unique accomplishment in determining a mechanical property, the lowest antisymmetric plate wave velocity, by totally noncontact means. A drawback was that it depended on the geometry of the specimen.

Figures 1 and 2 show a comparison of the experimental arrangements for the contact and noncontact methods of A-U. For the noncontact case (Fig. 2) the NdYAG pulse is directed downward by a 90 degree infrared prism to the point where, conventionally, the sending transducer is coupled by a dry couplant pad (Fig. 1). The air coupled transducer (Fig. 2) is placed so as to be sensitive to the point on the surface where, conventionally, the receiving transducer is coupled (Fig. 1). With this arrangement, the noncontact exactly replaces the contact measurement in terms of geometry. Note that the results described in [22] depend upon the laser pulse arrival at the edge of one end of the specimen.

The laser was single pulsed at approximately 13 mJ/pulse as calibrated by the energy sensor before passing through the prism. The prism attenuated 15 percent of the energy of the beam. The pulse energy was maintained at this same value for all the results presented here. This energy was judged to be well below the damage threshold for the materials studied. Although a damage threshold was not identified, repeated pulsing did not cause a permanent

change in the A-U signal in either material studied. In addition, a SiC/SiC specimen showed no metallographic changes after repeated pulsing at the 13 mJ.

The focused air-coupled piezoelectric transducers were broadband and centered nominally at 0.25, 0.5, 1.0, and 2.0 MHz. A 5.0 MHz focused transducer was also tried but was not successful. In each case they were coupled to the air through a buffer which had a concave shaped outer surface to focus the ultrasound 5.08 cm beyond the buffer surface. (The buffer material is held proprietary by the manufacturer.)

The micromachined, capacitance transducer consisted of a charged, metalized polymer film capacitor [24-27]. It was not focused and was placed about 0.5 cm above the specimen surface. This unit had a net response over the 0.1 to 2.0 MHz frequency range in which it was used.

Figure 3 illustrates the configuration employed with the (a) focused and (b) thin film air coupled transducers.

MATERIAL USED

SiC/SiC Ceramic Matrix Composites

For the work reported in [22], six SiC/SiC specimens composed of 3 lay-ups (0/90, ± 45 , and [0/+45/90/-45]) with approximately 20 percent porosity were studied. The average fiber content by volume was 40 percent. Each 1.27×15.24 cm specimen was cut from an 8 ply panel with an average thickness ranging from 0.25 to 0.29 cm. After being cut into rectangular bars they were treated with a seal coating. In the present work a single 0/90 eight ply specimen was measured.

SiC/Ti 6-4 Metal Matrix Composite

For the metal matrix composites, the UD rate measurements were performed on a single, [0] tensile specimen with a dog bone geometry. They were 15.2 cm long and 0.15 cm thick. The specimen's width was 1.2 cm at the grips and 0.95 cm in the gauge region.

RESULTS AND DISCUSSION

Detection of acousto-ultrasonic signals.—In preliminary experiments an attempt was made to detect both lowest symmetric and a lowest antisymmetric mode pulses from noncontact signals on a SiC/SiC specimen in the

geometric arrangement as with contact transducers [10]. Whereas the antisymmetric pulse was usually quite evident, the symmetric pulse was always absent. It is likely that the nature of these two modes is responsible for the different behavior [2]. The antisymmetric is a mixed shear-flexure mode and causes displacement normal to the surface. This is the direction for most easy radiation into the surrounding air. The symmetric mode is longitudinal and causes displacement parallel to the surface and may cause no radiation into the surrounding air.

Figure 4 shows an ultrasonic decay signal collected from the [0/90] SiC/SiC specimen employing laser in and a 0.25 MHz focused air coupled transducer out. With contact measurements on this type of specimen, it is typical to use 2.25 MHz and to collect a record length of about 500 μ sec. For the noncontact it is necessary to collect a record length of about 3-1/2 times as long due to the lower attenuation at this lower frequency in order to determine the ultrasonic decay rate with similar precision.

Determining UD rates.—The method for calculating UD rates has been detailed elsewhere [13]. An A-U waveform commonly consists of a dead time, until the earliest portion of the signal has crossed the sender to receiver space, followed by an initial rise, and completed by an exponential decay. It is the time decay of the power spectrum of this final segment that is the UD rate.

UD rates for the two materials are plotted in Figs. 5 to 8. In all cases, the point of introduction of ultrasound was about 3.2 cm from the point of detection, and centered on the gauge portion of the specimen. After collection of the first waveform the specimen was rotated 180 degrees and a second waveform collected with the position of ultrasound introduction and detection reversed. Two more waveforms were collected on the opposite face of the specimen in the same manner. This process was repeated three times for a total of twelve waveforms. The average and standard deviation of the twelve calculated decay rates are plotted in Figs. 5 to 8.

Figures 5 and 6 compare UD rates over a range of frequencies determined on a SiC/SiC [0/90] tensile specimen. It was possible to determine UD rates with contact transducers to at least 5 MHz. In the case of the noncontact it was possible to go as high as 1.8 MHz.

UD rate is higher for contact measurements than for noncontact. This is attributed to energy loss to the contacts. A component, attributed to energy loss at contacts, in the sum $\Sigma\beta_i(f)$ in Eq. (6) is not present for the noncontact measurements. This seems to imply that the noncontact rate is a more pure measure of attenuation within the specimen under study. Still, contact measurements have been successful in detecting mechanical fatigue in these materials [11-14]. It is important that this be so since projected uses of UD for monitoring the health of aircraft components will often be required to be sensitive in the presence of support structures that cause ultrasonic energy loss. Both the contact and noncontact methods exhibit $\beta(f)$ values that increase with frequency.

Figure 6 shows just the noncontact data with the [0/90] SiC/SiC. The micromachined capacitance transducer was placed 0.5 cm from the specimen and was useful out to about 1.8 MHz. The focused transducers were

5.08 cm from the specimen surface and were good only to 1.0 MHz. The difference in frequency range can be attributed to increased air attenuation for the latter. The fixed transducer distance was dependent on the focal length of the buffer. Of course there may be applications, such as in the presence of elevated temperature, where it is necessary to keep transducers at a safe distance. Under these conditions this advantage of the micromachined capacitance transducer would be less significant.

Similarly, Figs. 7 and 8 compare UD rates over a range of frequencies as determined on a SiC/Ti 6-4 [0] tensile specimen. The results are similar to the SiC/SiC specimen case. In Fig. 8 the focused transducers seem to be good only out to 0.4 MHz.

The difference here from the SiC/SiC is that the UD waveforms were of lower amplitude. For both specimens the laser pulse energy was 13 mJ. It is likely that a larger fraction of the laser energy was reflected back from the metal matrix surface than the ceramic. Pulsing at a higher energy may increase the frequency range in the metal matrix composite with the air coupled transducers.

Observed effect of the Laser pulse on the Specimen properties.—It was reported earlier [22] that repeated laser pulsing at the same location produced deterioration of the ultrasonic signal. After such repetitions the waveform amplitude would decrease. This again was observed on the SiC/SiC specimen. This effect was not studied in the SiC/Ti 6-4 specimen, however if it exists it is much smaller. This difference, if due to vaporization of a surface layer, would be expected to be more pronounced in the SiC/SiC as a result of their porosity and the corresponding greater surface area. The SiC/Ti 6-4 specimen has smooth surfaces and are essentially pore free. In the present work, satisfactory UD rates were determined from waveforms that were in the deteriorated state, as defined above. The 13 mJ pulse did not appear to cause permanent damage in any of these experiments. In a period of hours the waveform would return to its original magnitude. It is speculated that this may correspond to the reabsorption of a surface layer such as water vapor.

Earlier observations [19] demonstrated that a threshold for permanent damage exists in graphite fiber-reinforced PMR-11 and PMR-15 composites at laser energy below the present level. However, the energy density was higher since the original laser employed produced a small spot size. It is not clear whether total energy or energy density is the critical variable.

Another difference between contact transducer and laser generation of ultrasound may be the penetrating nature of the laser beam. In the contact case the ultrasound is always introduced at the specimen surface. We have noted earlier [19] that for the laser case, some of the NdYAG beam passes through the thickness of a polymer resin while producing ultrasound. This is probably more extreme than occurs in the present materials. Still, the SiC/SiC specimens are 20 percent porous, so some laser energy may penetrate. With the ultrasound appearing interior to the specimen a different mix of modes may be present than in the contact case.

CONCLUSIONS

Acousto-Ultrasonic signals, appropriate for determining ultrasonic decay rates, can be realized in SiC/SiC and SiC/Ti 6-4 composites by means of laser-in and air coupled out.

The NdYAG laser pulsed at 13 mJ provided thermoeelastic vibrations from at least 0.1 to 2.0 MHz.

The focused air coupled transducers had a range of 0.1 to no greater than 1.0 MHz under the present conditions. The micromachined capacitance transducer was usable from 0.1 to 1.8 MHz. The micromachined capacitance transducer might be the better choice to use when it can be placed close enough to the specimen to take advantage of its wider frequency range. If experimental considerations require a greater separation from the specimen the advantage diminishes.

The experimental coupons employed in this work tend to be about as thin as one is likely to encounter. Application to industrial quality control or hardware health monitoring would probably involve greater thicknesses and therefore lower frequencies for the same conditions. This seems to be advantageous for noncontact A-U since lower frequencies will allow recovery of stronger signals and thus greater precision.

Greater precision is also likely at higher laser pulse energies since it would lead to larger signal magnitude. These experiments, however, ought to be performed in conjunction with studies of laser damage thresholds.

It is important to conduct thermomechanical fatigue studies in conjunction with noncontact UD in order to compare sensitivity of this technique to that of contact UD in monitoring degradation in materials of interest.

Lowest symmetric mode pulses were not detectable under the present conditions. This may be due to the longitudinal orientation of this plate mode.

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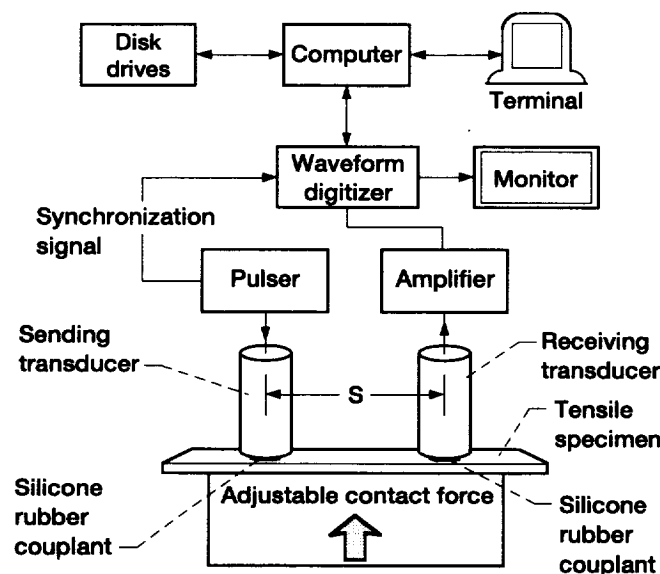


Figure 1.—Acousto-ultrasonic configuration employed for collecting data. S is the centerline spacing between the transducers.

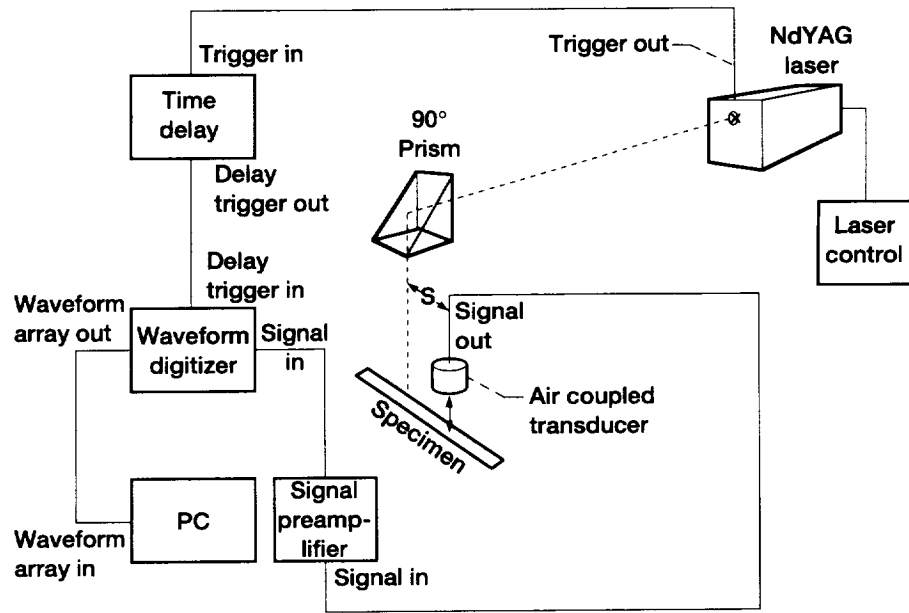


Figure 2.—Experimental arrangement for collecting laser in-air out acousto-ultrasonic waveforms.

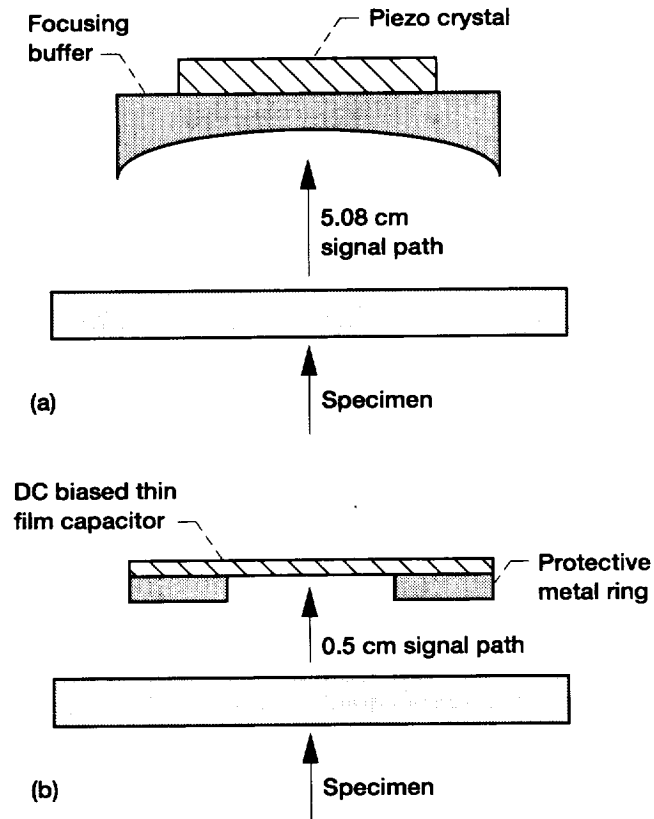


Figure 3.—Crosssection. (a) Focused transducer. (b) Micro-machined, thin film air coupled detecting transducers.

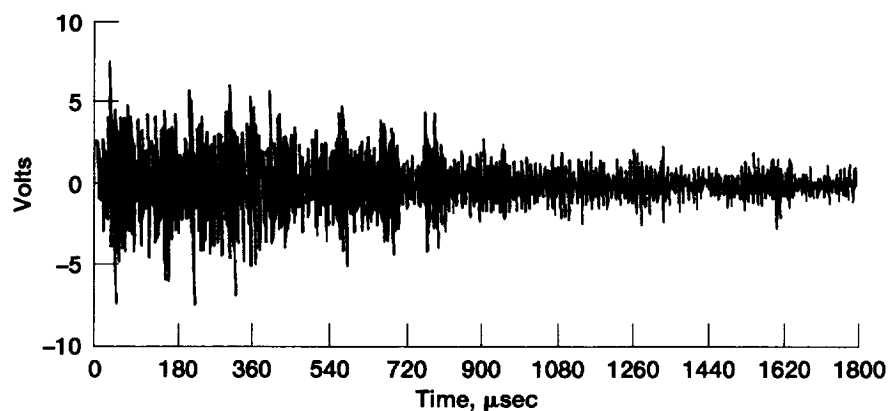


Figure 4.—Ultrasonic decay signal with laser-in 0.25 Mhz focused air coupled transducer-out

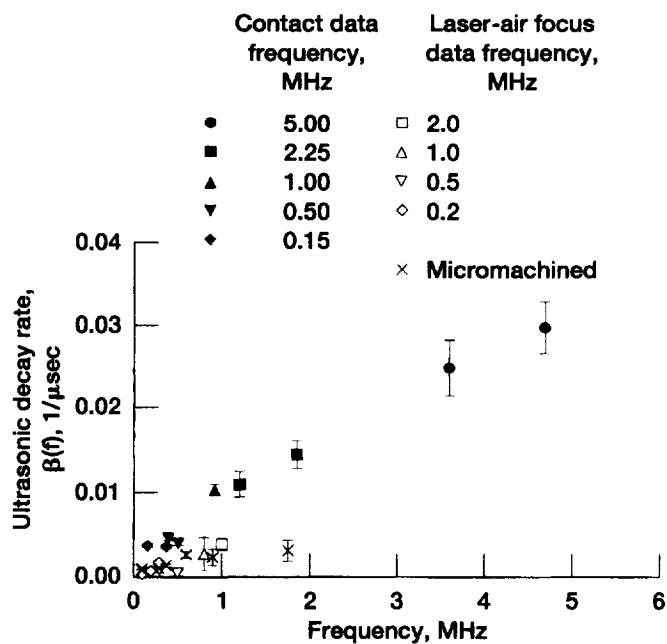


Figure 5.—Ultrasonic decay on SiC/SiC[0/90] comparing contact to laser-air data

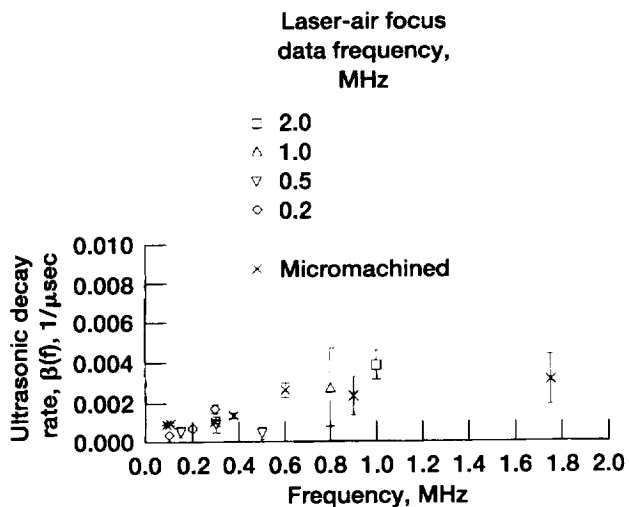


Figure 6.—Ultrasonic decay on SiC/SiC[0/90] noncontact laser-air data

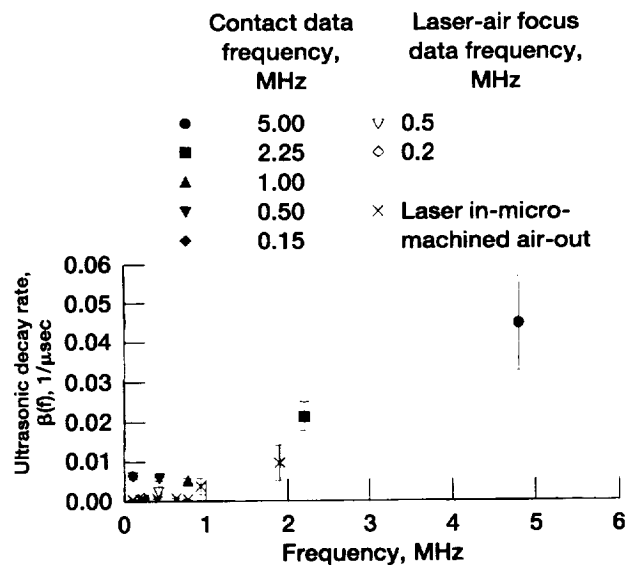


Figure 7.—Ultrasonic decay on SiC/Ti 6-4 alloy composite comparing contact to laser-air coupling

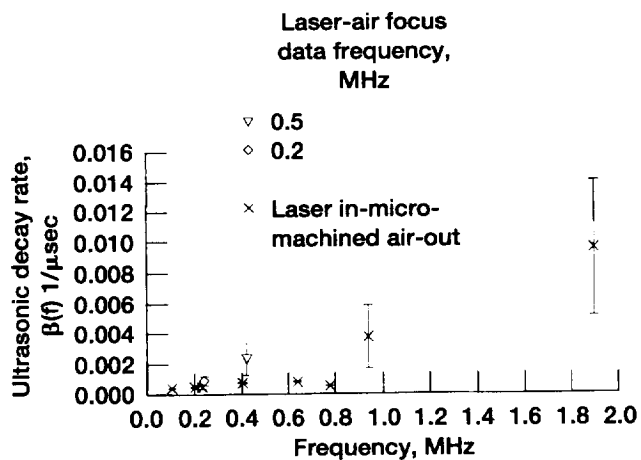


Figure 8.—Ultrasonic decay on SiC/Ti 6-4 alloy composite for laser-air coupling

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